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Analysis of a symbiotic thermoelectric system for power generation and liquid preheating

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HIGHLIGHTS

- A symbiotic TE system can generate electricity with no heat rejection.
- Overall thermal–electrical efficiency is the same as the heater's efficiency.
- A TE generator may be installed on a liquid heater as an "add-on" apparatus.

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ABSTRACT

Thermoelectrics have long been recognized as a unique energy conversion technology due to their capability to convert heat directly into electricity having no moving parts. Despite this potential, except for specialised situations, thermoelectric devices have limited applications because of their low efficiency. Generally they exhibit low conversion efficiency because of the relatively small figure-of-merit (*ZT*) of currently available thermoelectric materials. Many efforts have been made over recent years on improving thermoelectric conversion efficiency by increasing *ZT*, with only marginal success. In this research an alternative solution was provided to overcome the main drawback of thermoelectric devices. The idea is to operate the thermoelectric generator in a combined heat and power generation mode. This configuration consists of a stacked assembly of several thermoelectric modules sandwiched between three rectangular cold and hot liquid passages appropriately connected to an ordinary liquid (e.g. water) heater. It is shown that the combined system can produce heat and electricity with nearly zero heat dissipation to the surroundings by re-using rejected heat from thermoelectric modules for inlet liquid preheating.

1. Introduction

A thermoelectric generator is a unique heat engine, in which charge carriers serve as the working fluid. It can produce electricity through having a temperature difference across its sides [1]. Thermoelectric generators have several major advantages including being highly reliable, having no moving or complex parts, being environmentally friendly, being maintenance free and silent in operation, having no position-dependence, having long life cycles (more than 100,000 h steady-state operation), being light and having modular structure as well as adaptability to various sources and types of fuel [2]. Because of the advantages explained above, there has been worldwide emphasis on the development of thermoelectric generators for a variety of applications over recent decades [3].

However, except for specialised situations where reliability is a major concern like spaceship's power source, most recent developments in applications of thermoelectric generation in electrical power generation, have occurred in fields related to high temperature thermoelectric waste heat recovery through recovery of either exhaust heat in the automotive industry or emissions from industrial utilities since it is unnecessary to consider the cost of input thermal energy. Concentration on these areas is at the expense of the wider exploitations of thermoelectric conversion with other sources of thermal energy, and in particular natural occurring and low temperature heat, receiving little, if any, attention [4–6].

Fig. 1 shows the basic configuration of thermoelectric power generation. A thermoelectric module is sandwiched between a heat source and a heat sink. Heat flows from the hot side through the

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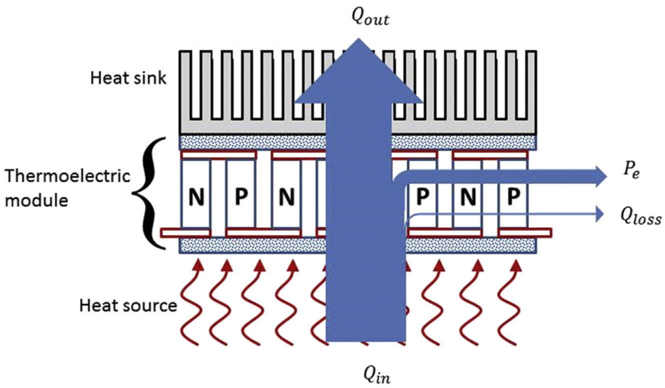

Fig. 1. Power distribution in a typical thermoelectric power generation system. Q_{in} is the heat supplied by the heat source, Q_{out} is the heat dissipated to the heat sink, P_e is the electrical power produced and Q_{loss} is the heat wasted through the sides of thermoelements to the surroundings.

module and is dissipated through the heat sink to the surrounding. This thermal energy movement excites thermoelement semiconductors and electrical power will be generated based on Seebeck effect. Conversion efficiency of a thermoelectric module can be a function of "goodness" of its semiconductor materials. Goodness or figure-of-merit of thermoelectric materials can be expressed as $Z = \alpha^2\sigma/\lambda$, where Z is a figure-of-merit, α the Seebeck coefficient and σ and λ are the electrical and thermal conductivities, respectively. This figure-of-merit can be made dimensionless through multiplying by the average temperature T of the sides of the module. In that case, $ZT = \alpha^2\sigma T/\lambda$. For the reason that the figure-of-merit of commercial thermoelectric materials are usually low ($ZT < 1$), a thermoelectric power generator exhibits low conversion efficiency. As over the past five decades, improvement in the efficiency of thermoelectric material has been marginal, many researches have been carried out to find methods to increase the conversion efficiency of thermoelectric power generation systems independent of the figure-of-merit of the thermoelectric material [7,8].

As an example, "waste heat" recovery is one of the promising areas where thermoelectric power generation can be economically competitive. As the supply of heat in the case of waste heat is almost free, conversion efficiency of the thermoelectric device is not a significant concern.

In addition to progress in the waste heat recovery area, the concept of "parasitic" or "symbiotic" application of thermoelectric conversion has been introduced by Rowe and Min in 2002 [7]. Through this method, a thermoelectric module is used as a generator and an efficient heat exchanger. In this approach, Q_{out} in Fig. 1, instead of being discharged to the surroundings, is absorbed by a liquid as a means of preheating. In this study, design, fabrication, analysis and discussion of a thermoelectric heat exchanger/power generator is presented.

2. Thermoelectric module for power generation and liquid pre-heating

Although there are obvious merits in thermoelectric waste heat recovery, the modules still dissipate a large portion of the absorbed heat to the ambient. In order to overcome this drawback, a system incorporating a heat exchanger and thermoelectric generator is introduced. Fig. 2 represents a cross section view of a system which is here called ELEGANT; an acronym from "Efficient Liquid-based Electricity Generation Apparatus iNside Thermoelectrics". In this configuration, thermoelectric modules are incorporated into a liquid heater by sandwiching modules between three aluminium channels. The middle channel, conducts hot liquid and heats the hot sides of the thermoelectric modules. The side channels conduct cold liquid and cool the cold sides of the thermoelectric modules. Although the main purpose of such a system is to produce hot liquid, a very small portion of heat from the outlet of the heater will flow through a bypass, consisting of the thermoelectric modules, and will be converted to electricity. The advantage of this cogeneration system is that the heat dissipated from modules returns to the system through preheating the inlet liquid.

While there may exist other thermoelectric cogeneration systems that use dissipated heat from thermoelectric power generator to heat a liquid, the main advantage of this system is that the system can be used as an "add-on power generator" so that no alterations in the system have to be made [9].

For the heating system without thermoelectric modules and ignoring heat loss, the overall efficiency of heat production is the efficiency of the liquid heater. It is given by,

$$\eta_{th} = \frac{Q_h - Q_c}{W_1} \tag{1}$$

where η_{th} is the thermal efficiency of the system without thermoelectric modules. Q_h–Q_c and W_1 are the amount of heat produced and input energy to the heater, respectively. In the case of considering thermoelectric modules and ignoring heat loss, Q_{loss}, wasted through the sides of thermoelectric modules the efficiency of total energy production (thermal and electrical) can be expressed as:

$$\eta_{to} = \frac{Q_{ho} - Q_c + 2P_e}{W_2} \tag{2}$$

where Q_{ho} is the heat energy carried out of the system by liquid, W_2 is the energy input related to the new configuration (incorporating thermoelectric modules) and P_e the electrical power generated by thermoelectric modules. It can be seen from Fig. 2 that,

$$Q_h - Q_{ho} = 2Q_{hc} + 2P_e \tag{3}$$

If we assume that the efficiency of the heater is independent of the inlet liquid temperature, it will remain unchanged regardless of preheating. Therefore,

$$\eta_{th} W_2 = Q_h - (Q_c + 2Q_{hc}) \tag{4}$$

Using Equations (1) and (4),

$$W_2 = \frac{Q_h - Q_c - 2Q_{hc}}{Q_h - Q_c} W_1 \tag{5}$$

Finally using Equations (1), (3)–(5),

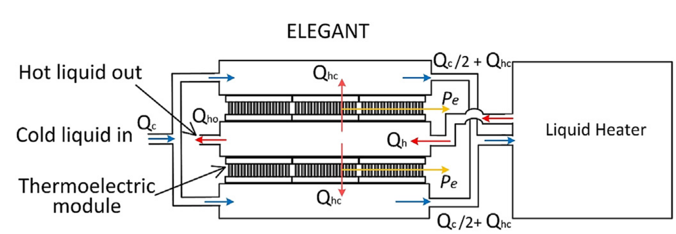

Fig. 2. Cross section view of ELEGANT. The heat dissipated from thermoelectric modules (Q_{hc}) is not wasted. Instead, it is used to preheat the cold liquid (heat wasted through sides of thermoelectric modules, Q_{loss} is assumed to be negligible).

$$\eta_{to} = \frac{Q_{ho} - Q_c + 2P_e}{W_2} = \frac{Q_{ho} - Q_c + 2P_e}{\frac{Q_h - Q_c - 2Q_{hc}}{Q_h - Q_c} W_1} = \frac{Q_h - Q_c - 2Q_{hc}}{\frac{Q_h - Q_c - 2Q_{hc}}{Q_h - Q_c} W_1} = \frac{Q_h - Q_c}{W_1} = \eta_{th} \tag{6}$$

The above expression shows that the overall efficiency (including both heat production and power generation) of this cogeneration system, ignoring heat losses, is the same as that of the heat source without incorporating thermoelectric modules. This can be a step toward overcoming the drawback of low efficiency of thermoelectric generator systems.

3. System modelling

A one-dimensional steady-state model has been developed in order to estimate the output power of an ELEGANT supplied by hot and cold water and compared with a conventional thermoelectric power generation system with parallel plate heat exchangers. In this model an ELEGANT-24 with the following details has been proposed:

- Three rectangular aluminium tubes.
- 24 commercial thermoelectric modules (TEG).
- A resistive load equivalent to the sum of effective internal electrical resistances of thermoelectric modules.

The middle channel is a passage for hot water and two other channels carry cold water. TEGs are sandwiched between the hot and cold channels using a clamping mechanism with proper compression force. Fig. 3 shows a basic diagram of the configuration. The TEGs are connected electrically in series.

In order to simplify the model the following assumptions are made:

a) Heat convection losses between the tube surfaces and the surroundings are ignored (system well insulated). Radiation losses are also ignored.
b) Air gaps between thermoelectric modules and tubes' surfaces are negligible.
c) Thermal resistance of each thermoelectric module is considered the same and heat flux through them is uniform.
d) Heat losses through side surfaces of thermoelectric modules are ignored.
e) Average thermal resistance of each TEG module is known through other single-module tests.

Based on these considerations, liquid temperature changes along the liquid passages and the temperature difference across the thermoelectric modules used to generate electricity have been analysed. Associated with proposing a new symbiotic configuration of flat plate heat exchangers, this work is intended to simulate

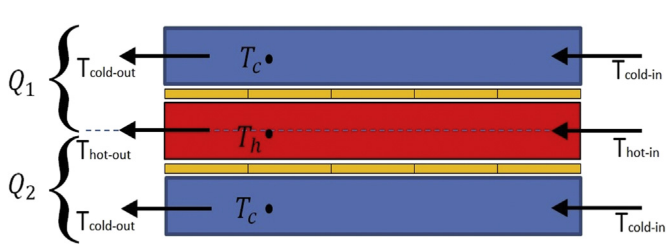

Fig. 3. Thermal model for the ELEGANT. Assuming symmetrical flow, Q_1 is equal to Q_2.

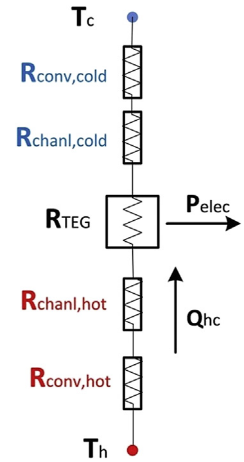

Fig. 4. Thermal resistance model for half of the ELEGANT.

output electrical power of ELEGANT-24, in terms of the characteristics of the inlet flow. Using symmetry, by calculating output of the top rows of the TEGs (half of the system) and doubling the result, the overall power can be obtained.

It is known that, electrical power output of a thermoelectric module is a function of the temperature difference between the hot and cold sides. TEG output power as a function of temperature difference can be measured through experiment (or supplied by the manufacturer). Alternatively, knowing thermal resistance and heat flux through a thermoelectric module, the temperature difference can be readily calculated.

In order to design or to predict the performance of a heat exchanger, it is essential to relate the total heat transfer rate to quantities including the inlet and outlet liquid temperature, the overall heat transfer coefficient, and the total surface area for heat transfer [10]. The two main methods for this type of analysis are the Log Mean Temperature Difference (LMTD) method and the Effectiveness-NTU method [11]. In this study using the first method (LMTD), outlet temperatures for cold and hot channels are predicted and then through applying an effective thermal resistance model and simulating temperature difference across TEGs with reference to the performance curve of the TEG, the output power of ELEGANT is predicted.

With the stated assumptions the following equations may be used to determine the outlet temperatures of hot and cold liquids [12]:

$$T_{ho} = \frac{T_{hi}\cdot(B-1) - B\cdot T_{ci}\left[1 - \exp\left[U_oA_o(B-1)/(\dot{m}_c\cdot C_{pc})\right]\right]}{B\cdot\exp\left[U_oA_o(B-1)/\dot{m}_c\cdot C_{pc}\right]} \tag{7}$$

where

$$B = \frac{\dot{m}_c\cdot C_{pc}}{\dot{m}_h\cdot C_{ph}} \tag{8}$$

and where T_{ho}, T_{hi} and T_{ci} are hot liquid outlet temperature, hot liquid inlet temperature and cold liquid inlet temperature, respectively. In this expression, $\dot{m}_c$, $\dot{m}_h$, C_{pc} and C_{ph} represent cold flow-rate, hot flow-rate, specific heat capacity of cold liquid at inlet temperature and specific heat capacity of hot liquid at inlet temperature, respectively. U_oA_o is calculated from the following expression [12]:

$$U_o A_o = \frac{1}{R_{\text{eff}}} \tag{9}$$

where R_{eff} is the total thermal resistance between the hot liquid and the cold liquid with the liquids passing through channels of constant flow rate and at given flow rate and temperature.

The outlet cold liquid temperature, T_{co}, is calculated by:

$$T_{\text{co}} = T_{\text{ci}} + \frac{T_{\text{hi}} - T_{\text{ho}}}{R} \tag{10}$$

To determine R_{eff}, components of thermal resistance between hot and cold liquids are as shown in Fig. 4.

The basic heat transfer equation may be written as:

$$Q_1 = \frac{T_h - T_c}{R_{\text{eff}}} \tag{11}$$

where Q_1, T_h, T_c and R_{eff} are total heat transferred from hot channel to upper cold channel, inlet temperature of hot liquid, inlet temperature of cold liquid and total thermal resistance between hot and upper cold channels, respectively. To simplify the model, total thermal resistance along one TEG module, R_{total}, and then R_{eff} can be determined by considering 12 equal thermal resistances in parallel. To calculate R_{total}:

$$R_{\text{total}} = R_{\text{conv, cld}} + R_{\text{chanl, cld}} + R_{\text{TEG}} + R_{\text{chanl, hot}} + R_{\text{conv, hot}} \tag{12}$$

where

$$R_{\text{chanl, cld}} = R_{\text{chanl, hot}} = \frac{L}{k \cdot A} \tag{13}$$

where L is thickness of the channel wall, k is thermal conductivity of material of the pipe wall material and A is the area of pipe surface in contact with one thermoelectric module. In addition:

$$R_{\text{conv, cld}} = \frac{1}{h_c \cdot A} \tag{14}$$

where h_c is the convective heat transfer coefficient of liquid in the cold channel and A is the internal cross sectional area of the cold channel. To calculate h_c, Reynolds number, R_e, needs to be calculated. Reynolds number may be calculated using the following expression [10]:

$$R_e = \frac{\rho \cdot V \cdot D_h}{\mu} \tag{15}$$

where ρ is density of liquid, V is mean velocity of liquid through the pipe, D_h is hydraulic diameter which is equal to 4 times A divided by the internal wetted perimeter of the cold channel and μ which represents viscosity of the liquid. For $R_e > 2000$ flow is treated as laminar and with $R_e > 4000$ flow is turbulent. In the following calculations, turbulent flow conditions are selected as $R_e > 4000$ at the selected operating conditions. Therefore friction factor (f) is calculated by Ref. [10]:

$$f = (0.79 \ln R_e - 1.64)^{-2} \quad @R_e > 4000 \tag{16}$$

Knowing the friction factor and obtaining the Prandtl number (Pr) from the fluid specification table, the Nusselt number (Nu) may be calculated, where [10]:

$$\text{Nu} = \frac{\left(\frac{f}{8}\right)(R_e - 1000)\text{Pr}}{1 + 12.7\left(\frac{f}{8}\right)^{0.5}\left(\text{Pr}^{\frac{2}{3}} - 1\right)} \tag{17}$$

Also it is known that [10]:

$$\text{Nu} = \frac{h_c \cdot D_h}{k} \tag{18}$$

Using Equations (16)–(18), h_c can be calculated. Equation (14) will then provide the value of $R_{\text{conv, cld}}$. The value of $R_{\text{conv, hot}}$ may be calculated in the same way.

These results relates to half of ELEGANT-24 and as there are 12 theoretically similar TEG modules connected thermally in parallel, the total thermal resistance of this section may be evaluated as

$$R_{\text{eff}} = \frac{R_{\text{total}}}{12} \tag{19}$$

Using Equations (7) and (19)

$$T_{\text{ho}} = \frac{T_{\text{hi}} \cdot (B-1) - B \cdot T_{\text{ci}}\left[1 - \exp\left[R_{\text{total}}(B-1)/(12\dot{m}_c \cdot C_{\text{pc}})\right]\right]}{B \cdot \exp\left[R_{\text{total}} \cdot (B-1)/(12\dot{m}_c \cdot C_{\text{pc}})\right]} \tag{20}$$

Using the LMTD method, the average temperature difference across each TEG, ΔT_{TEG}, is calculated as

$$\Delta T_{\text{TEG}} = \frac{\Delta\text{LMTD}(T_{\text{hi}}, T_{\text{ho}}, T_{\text{ci}}, T_{\text{co}})}{R_{\text{eff}}} \cdot R_{\text{TEG}} \tag{21}$$

The output power of a TEG, P_{TEG}, is a function of the temperature difference across TEG, or

$$P_{\text{TEG}} \equiv f(\Delta T_{\text{TEG}}) \tag{22}$$

Thus the total output power of ELEGANT-24, P_{elec}, can be calculated by:

$$P_{\text{elec}} = \sum_{i=1}^{24} P_{\text{TEG}(i)} = 2\sum_{i=1}^{12} f_i(\Delta T_{\text{TEG}}) \tag{23}$$

To evaluate performance of ELEGANT-24 in conjunction with a heater, a thermal liquid heater was added to the model.

Thermal efficiency of the liquid heating system without ELEGANT-24, η_{th}, can be expressed as:

$$\eta_{\text{th}} = \frac{\Delta Q}{W_1} \tag{24}$$

where W_1 is input thermal power to the heater. Considering the preceding discussion and equations this can also be written as:

$$\eta_{\text{th}} = \frac{\dot{m} \cdot C_p \cdot (T_{\text{out}} - T_{\text{in}})}{W_1} \tag{25}$$

In the case of connecting ELEGANT-24 to the heater, new thermal-electrical efficiency, η_{to}, can be defined as:

$$\eta_{\text{to}} = \frac{\Delta Q_1 + P_{\text{elec}}}{W_1} \tag{26}$$

where ΔQ_1 and P_{elec} are new changes in the rate of energy carriage by the liquid and generated electricity, respectively. In the case of

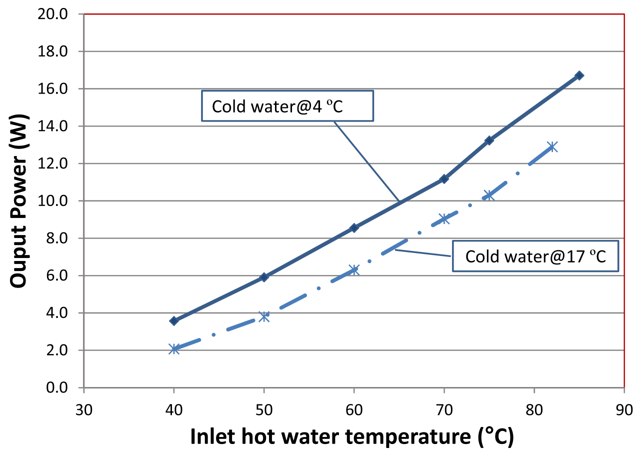

Fig. 5. Theoretical output power of ELEGANT-24 as a function of inlet hot water temperature before considering the heater. Inlet cold water temperature was kept constant at 4 °C and 17 °C.

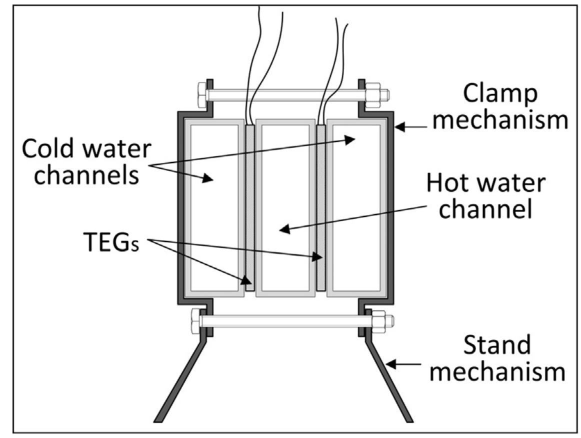

Fig. 7. A cross section view of the ELEGANT. For the sake of clarity, thermal insulations are not shown.

no change to the flow rate and input thermal power, Equation (26) may be written as:

$$\eta_{to} = \frac{\dot{m} \cdot C_p \cdot (T_{ho} - T_{ci}) + P_{elec}}{W_1} \tag{27}$$

where T_{ho}, T_{ci} and P_{elec} are outlet hot liquid temperature, inlet cold liquid temperature and total electric power respectively produced by the ELEGANT-24.

For model simulation all equations were entered to an Excel spread sheet. Input data include configuration parameters of the channels, thermophysical properties of the liquid and channels, as well as inlet liquid temperatures and inlet mass flow rate. The model was run under steady state.

4. Simulation results

Distilled water was selected as the working fluid and 24 commercial thermoelectric with dimension of 40 mm by 40 mm, average thermal resistance of 1.2 °C/W and average electrical resistance of 2 Ω are considered. The external resistive load is assumed to be equivalent to the sum the internal resistances of the TEG's with a value of 48 Ω in order that the maximum output power of the TEG modules could be achieved. A numerical table of output power as a function of temperature difference across TEG was produced by using data from a TEG real test. Three supposed channels have the same geometry of 480 mm (L) by 40 mm (W) by 12 mm (H) and 1 mm wall thickness made of aluminium. These dimensions were chosen including taking into account the dimensions of commercial TEG modules and constraining turbulent flow conditions in the channels within an acceptable flow rate in order to provide a good heat transfer coefficient. The thermophysical properties of the TEG and channels are treated as being constant during the heat transfer process. Thermal convection between channels to the surroundings and heat transfer perpendicular to the direction to TEG free surfaces are considered negligible. The inlet water flow rate and thermal efficiency of the heater are held constant, but the inlet water temperature is selected as a variable parameter for different analytical cases. In all simulation cases the water flows through the channels at atmospheric pressure. The Prandtl number, viscosity, specific heat capacity, density and thermal conductivity of the water at different temperatures are determined through interpolation using the data table referred to in Ref. [10].

The simulation was carried out only for counter flow type heat exchangers as this type of heat exchanger creates a close to constant temperature difference across the TEGs along the heat exchanger length [13]. Fig. 5 shows results achieved from running the model with inlet hot water temperatures between 40 °C and 85 °C and the mass flow rate kept constant at 0.15 kg/s while inlet

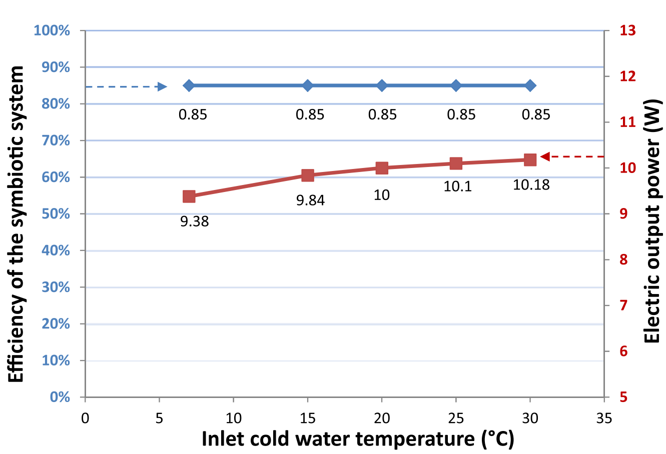

Fig. 6. Theoretical efficiency of the entire system (ELEGANT-24 connected to the heater) and electrical output power of the system as a function of inlet cold water temperature.

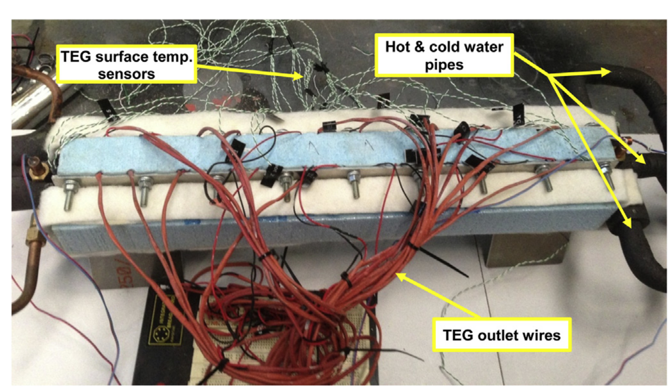

Fig. 8. A top view of ELEGANT-24 indicating TEG outlet wires connected to an electronic breadboard and thermocouple wires for TEG surface temperature measurement.

Table 1
Physical and electrical characteristics of the thermoelectric module. It is assumed that all 24 thermoelectric modules used in ELEGANT-24 are identical.

Brand and model	Internal electric resistance (Ω)	Thermal resistance (°C/W)	Dimension (mm)	Number of thermoelements	Semiconductor material
Huimao; 127-10T-125	≈2	≈1.2	40 * 40 * 3.9	127	Alloy of Bi–Te

cold water was kept constant at 4 °C and 14 °C. In the experiments which Fig. 6 represents their results, a heater with thermal input power of 40 kW and the thermal efficiency of 85 percent was considered.

5. Experimental study of ELEGANT-24

5.1. Experimental set up

In order to validate the theoretical model, a real ELEGANT-24 was built. It consists of three rectangular aluminium tubes and 24 thermoelectric modules. Two rows of thermoelectric modules, each including 12 modules, were sandwiched between aluminium channels using a clamping mechanism as shown in Fig. 7. This Figure also shows other details of the configuration.

Two 1–20 l/min Grundfos electronic flow-sensor were utilized for measuring the hot and cold water flow rate. Fig. 8 shows a top view of ELEGANT-24 experimental rig.

Tables 1 and 2 show characteristics of utilized TEGs and aluminium channels. To apply load to the output of TEGs, a dc electronic load, BK-Precision 8540, with maximum power of 150 W were used. This load operates in a range of 0.1 Ω to 4 KΩ to apply different values of DC load to the modules.

A closed loop water cooler-heater system including necessary storage tanks, feeding pumps, valves and temperature controllers (referred to as "heat bench") was used for supplying the cold and hot water to the ELEGANT-24.

T-type and K-type thermocouple wires were used for continues temperature sensing. The voltage and the power produced by TEGs, flow-related voltage generated by the flowmeters, inlet and outlet liquid temperatures, thermoelectric module surface temperature and ambient temperature were logged using an Agilent 34972 data logger and its associated software, BenchLink Data Logger 3.

5.2. Experimental procedure and results

To measure output power of a real ELEGANT-24 in order to validate theoretical model, some experiments have been conducted using hot and cold water on counter-flow basis. During this experiments water mass flow rate was held constant – at 0.15 kg/s. External electric load was designed to be equal to the sum of internal resistances of TEGs. During performing experiments the value of this resistive load was manually adjusted between 49 Ω and 50.1 Ω to collect maximum output power. The ELEGANT-24 output power was recorded at different inlet hot water temperature while the inlet cold water temperature was kept constant at two different temperatures, 4 °C and 17 °C. Fig. 9 shows results achieved from performing experiments with inlet cold water temperature at 4 °C and 17 °C. Figs. 10 and 11 illustrate a comparison between results of experimental work and prediction model.

Table 2
Physical characteristics of the fluid channels. It is assumed that all three channels used for conducting liquids have the same characteristics.

Type	Material	External dimension (mm)	Wall thickness (mm)	Surface roughness (μm)
Rectangular channels	Aluminium	500 * 250 * 20	3	0.1

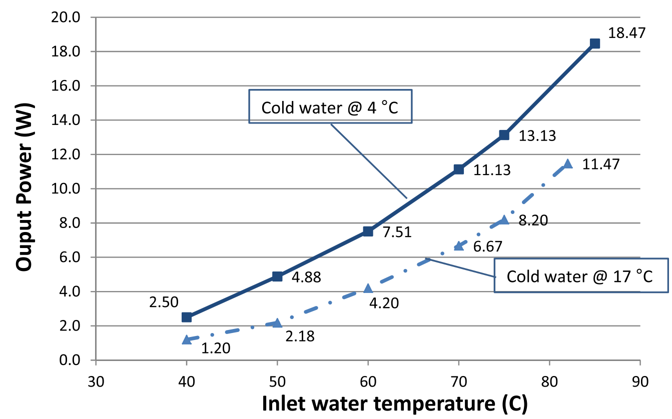

Fig. 9. The experimental output power of ELEGANT-24 as a function of inlet hot water temperature with inlet cold water was held constant at 4 °C and 17 °C.

6. Discussion and conclusion

It has been firmly established that thermoelectric modules are more efficient for coolling rather than generation [14] however here it is shown that a particular combination of thermoelectric modules and liquid passages in a compact configuration can generate electricity efficiently. A thermoelectric assembly comprising 24 commercial thermoelectric modules was designed and fabricated. The configuration is mainly applicable for symbiotic applications. A theoretical model was developed to analyse the system and some experiments were conducted in order to validate the model.

As it can be seen from Figs. 10 and 11, although the same trend is observed for theoretical are experimental results, curves are not matched. In Fig. 11 where the cold water temperature was held constant at 17 °C, predicted curve shows a close to 29 percent higher output power in compare with the experimental curve. This deviation in the experiment with cold water at 4 °C is around 15 percent. This is predominantly because of imperfect thermal insulation of the ELEGANT-24 so that the coolant (cold water) will

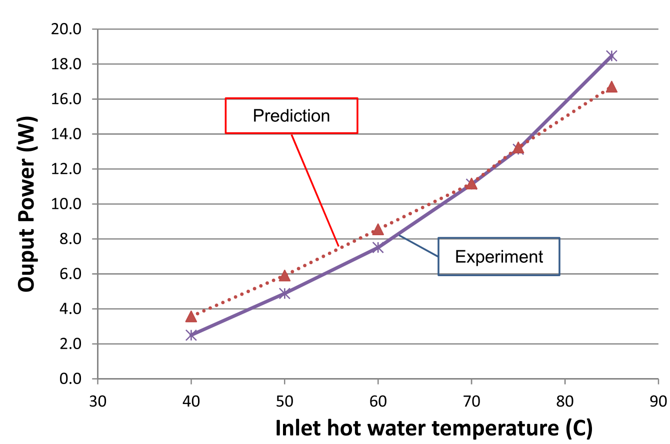

Fig. 10. A comparison between experimental and theoretical output power of ELEGANT-24 as a function of inlet hot water temperature with inlet cold water was held constant at 4 °C.

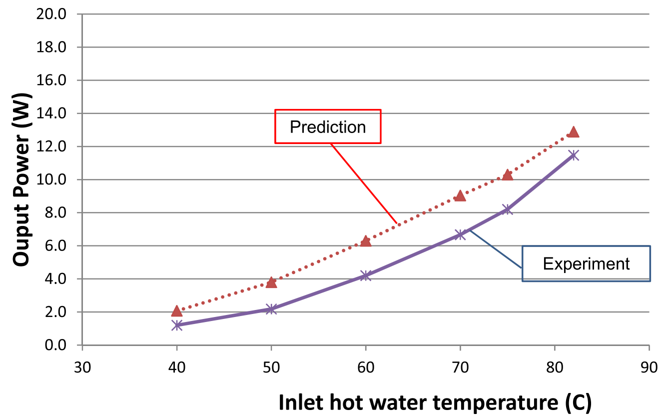

Fig. 11. A comparison between experimental and theoretical output power of ELEGANT-24 as a function of inlet hot water temperature with inlet cold water was held constant at 17 °C.

gain heat from surroundings and causes temperature difference reduction across TEG modules. This undesirable thermal convection also happens for the hot channel since hot water loses heat through thermal convection between aluminium channel and the surroundings.

It is also seen that a dissimilar power offset between theoretical and experimental results in the same temperature difference. An explanation of it might be that of some thermal characteristics of TEGs were neglected in the theoretical model.

Ideally, with a given temperature difference across a thermoelectric module, more power might be generated if the cold side temperature kept in the lower temperature [15]. To avoid complexity, the effect of cold side temperature on the conversion efficiency of TEGs was ignored within theoretical model. Therefore the actual produced power curve and predicted power curves, with cold water at 4 °C, have less offset in compare with that of those with cold water kept constant at 17 °C.

Therefore it can be concluded that the theoretical model is valid at certain temperature range.

This study showed that the drawback of thermoelectric relatively low conversion efficiency can be overcome by integrating thermoelectric modules with a conventional liquid heater system based on the concept of symbiotic generation. This happens *via* recycling the heat rejected form thermoelectric modules and preheating inlet liquid to the heater.

It is also shown that a specific symbiotic thermoelectric system, referred to as ELEGANT, in-line with inlet cold water and outlet hot water of an ordinary liquid heater can generate electricity without affecting total thermal efficiency of the system. In general, there is a large amount of heat dissipated from the cold side of a conventional thermoelectric generators, however this is not the case with the ELEGANT symbiotic system.

This thermoelectric power generation system can be used with liquid heating systems especially environmentally friendly heating systems like solar thermal collectors. Although the thermal efficiency of some renewable energy powered heaters like solar thermal heaters are affected by the inlet liquid temperature so that preheating of the inlet liquid may reduce thermal efficiency of the solar heating system, this doesn't mean that the proposed system cannot be used in conjunction with a solar thermal system. There are still several advantages for electricity generation through this method, such as hassle-free installation, quietness, reliability and long life span.

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